# SPIN GAPLESS SEMICONDUCTORS FOR SPINTRONIC APPLICATIONS

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## ABSTRACT

Spin gapless semiconductors (SGS) have emerged as a promising class of materials for advancing spintronic technologies due to their unique electronic and magnetic properties. Unlike conventional semiconductors, SGS materials exhibit a gapless band structure in one of the spin channels, offering high spin-polarized conduction with zero spin gap at the Fermi level. This distinctive feature makes SGS particularly attractive for spintronic applications such as spin field-effect transistors (Spin-FETs), magnetic memory devices, and quantum computing technologies. This review provides an in-depth examination of the properties of SGS, their potential in spintronic devices, and recent advances in material engineering. We discuss the latest experimental progress, challenges in synthesis and stability, and the integration of SGS into spintronic device architectures. Furthermore, we highlight the future prospects of SGS in revolutionizing next-generation low-power, high-efficiency spintronic applications. By reviewing the current state of SGS research, this article aims to underscore the pivotal role these materials could play in the development of future spintronic technologies.

**KEYWORDS:** Spin Gapless Semiconductors (SGS), Spintronics, Spin Polarization, Heusler Alloys, Spin Field-Effect Transistors (Spin-FETs), Quantum Computing

## 1. INTRODUCTION

Spintronics, or spin-based electronics, is an emerging field that exploits the intrinsic spin of electrons, in addition to their charge, for information processing and storage. The ability to control electron spin has opened up new avenues for the development of devices with superior performance characteristics, such as faster speeds, lower power consumption, and non-volatile memory capabilities. Central to the success of spintronic devices is the efficient generation, manipulation, and detection of spin-polarized currents. This has led to the exploration of new materials that offer optimal spin transport properties [1 - 3]. One such class of materials that has garnered significant attention in recent years is *Spin Gapless Semiconductors* (SGS) [4 - 6].

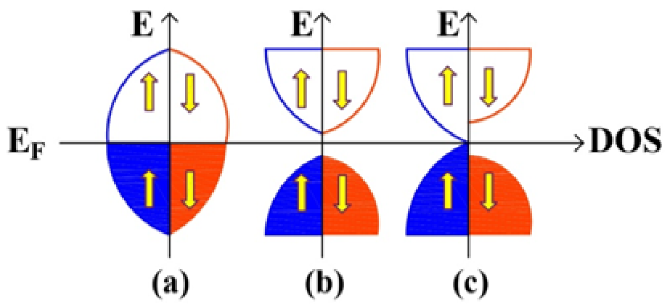



**Fig. 1: Schematics of density of states (DOS) for a typical (a) metal, (b) semiconductor, (c) spin gapless semiconductor. $E_F$ is the Fermi level.**

SGS materials are characterized by a unique electronic structure where the spin gap at the Fermi level is effectively zero in one spin channel and in the other channel it has a finite gap, meaning that spin-polarized conduction can occur without the need for an external magnetic field. The schematic plot of density of states for a normal metal, semiconductor and a SGS is shown in the Fig. 1. This feature sets SGS apart from traditional semiconductors and ferromagnetic materials, which typically require a spin-polarized current for efficient spintronic operation. As a result, SGS materials hold significant promise for advancing various spintronic applications, including spin field-effect transistors (Spin-FETs), magnetic memory devices, and even quantum computing [4, 7].

The unique properties of SGS—such as their high spin polarization, gapless spin transport, and tunable electronic characteristics—make them attractive candidates for next-generation spintronic devices. However, despite the potential advantages, challenges remain in terms of material synthesis, stability, and integration into practical devices [5,7]. This review aims to provide a comprehensive overview of the properties, advancements, and challenges associated with SGS materials, with a focus on their application in spintronic technologies. By summarizing recent research and highlighting future directions, this article seeks to demonstrate the crucial role SGS materials may play in the evolution of spintronic devices and their integration into future technological innovations.

## 2. MATERIALS AND METHODS

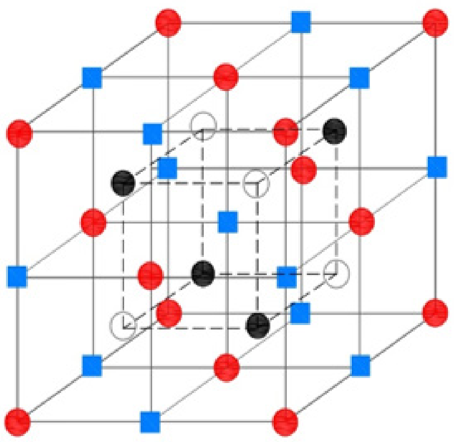
The study of Spin Gapless Semiconductors (SGS) involves the exploration of various materials with distinct electronic and magnetic properties. These materials are typically characterized by their gapless spin structure, which allows for efficient spin

transport. In this section, we summarize the key materials used for SGS research and the methods employed to synthesize and characterize these materials [8 - 11].

### 2.1. Materials

#### *2.1.1. Heusler Alloys:*

Heusler alloys, an interesting class of intermetallics exhibiting numerous stoichiometries (1:1:1, 2:1:1, 1:1:1:1), have been widely studied as potential SGS materials due to their tunable electronic and magnetic properties. Heusler alloys can be categorized mainly in two groups; one with the stoichiometry 1:1:1 (represented by XYZ and known as half-Heusler) and other with the stoichiometry 2:1:1 (represented by X2YZ and known as full Heusler). There is another group of alloys called inverse Heusler alloys in which atomic number of X is smaller than that of Y from the same period (i.e. Z(X) < Z(Y)). In recent times, quaternary Heusler alloys (XX′YZ) with the stoichiometry 1:1:1:1 have drawn enormous attention due to their exciting properties. In general, X and Y are transition metals or rare earth elements and Z is a main group (s-p) element. The structures of these four types of Heusler alloys are shown in the Fig. 2.



| Different Heuslers | General Formula | Space Group | Site Occupancy A | B | C | D |
|---|---|---|---|---|---|---|
| Half Heuslers | XYZ | F-43m (216) | X | Y | | Z |
| Full Heuslers | $X_2YZ$ | Fm-3m (225) | X | Y | X | Z |
| Quaternary Heuslers | XX'YZ | F-43m (216) | X | Y | X' | Z |
| Inverse Heuslers | $X_2YZ$ | F-43m (216) | X | X | Y | Z |

**Fig. 2: Heusler structures depending on the site occupancy of the constituent elements X, X′ , Y and Z at four different Wyckoff sites A, B, C and D.**

Examples of Heusler alloys investigated for SGS properties include Mn2CoAl [11], CoFeMnSi [9], CoFeCrGa [10], Co2MnSi [12] and $Co_2FeSi$ [12]. These materials can be optimized by varying their composition, which affects their band structure and spin-polarization characteristics.

#### *2.1.2. Transition Metal Compounds:*

Other transition metal-based materials such as Fe3O4 (magnetite), Cr-doped systems, and certain binary or ternary alloys of manganese, iron, and chromium have also been explored for SGS behaviour. These compounds are attractive due to their inherent magnetic properties and the ability to fine-tune their electronic structure through doping or alloying.

#### *2.1.3. 2D Materials and Heterostructures:*

Recently, two-dimensional (2D) materials, such as graphene, topological insulators, and transition metal dichalcogenides (TMDs), have been studied in the context of SGS properties. These materials, when combined with SGS materials in heterostructures, offer a new avenue for improving the spin transport properties, as well as enabling novel device concepts.

By constructing heterostructures, such as SGS/graphene or SGS/2D magnetic materials, researchers aim to take advantage of the unique properties of each material and enhance spin injection, transport, and detection.

### 2.2. Methods

The investigation of SGS materials involves both theoretical and experimental approaches. A combination of computational modelling, material synthesis, and characterization techniques is required to understand the properties of SGS and their suitability for spintronic applications.

#### *2.2.1. Theoretical Modelling and Simulations:*

Density Functional Theory (DFT) and other first-principles computational methods are commonly employed to predict the electronic structure of SGS materials. DFT simulations allow researchers to study the spin-resolved density of states, band structure, and spin-polarization of candidate materials. These models are crucial in understanding the behaviour of SGS under various conditions and guiding the design of new materials with optimized properties.

Additionally, tight-binding models, Monte Carlo simulations, and other computational approaches are used to investigate the spin transport properties, including spin diffusion length, spin relaxation times, and spin polarization efficiency.

#### *2.2.2. Material Synthesis:*

**Solid-State Synthesis:** Many SGS materials, particularly Heusler alloys, are synthesized using solid-state reaction methods, which involve high-temperature annealing of metal powders. The stoichiometric mixture of elements is heated at controlled temperatures to form the desired alloy phase. Precise control of temperature and time is essential to achieving the correct crystal structure and optimizing the SGS properties.

**Thin Film Deposition:** For device integration, SGS materials are often fabricated as thin films using techniques such as sputtering, molecular beam epitaxy (MBE), or chemical vapor deposition (CVD). Thin film deposition allows for precise control over the material's thickness and structural properties, which is crucial for ensuring the appropriate spin transport characteristics.

**Doping and Alloying:** The properties of SGS materials can be tuned by introducing dopants or by alloying different elements. For example, introducing elements like chromium or titanium into Heusler alloys can modify their electronic structure and enhance their gapless spin transport behaviour. Controlled doping and alloying are essential strategies for optimizing the performance of SGS materials in spintronic devices.

***2.2.3. Characterization Techniques:***

**X-ray Diffraction (XRD):** XRD is widely used to determine the crystal structure of SGS materials. This technique provides information on the phase composition, lattice constants, and crystallinity, which are important for understanding the material's electronic and magnetic properties.

**Magnetization Measurements:** Techniques such as vibrating sample magnetometry (VSM) or superconducting quantum interference device (SQUID) magnetometry are used to characterize the magnetic properties of SGS materials. These measurements provide insight into the spin polarization, magnetic ordering, and magnetic susceptibility, which are critical factors for spintronic applications.

**Spin-Resolved Photoemission Spectroscopy (ARPES):** Angle-resolved photoemission spectroscopy (ARPES) is employed to directly probe the electronic band structure and spin-polarization of SGS materials. ARPES allows researchers to observe the spin-polarized states at the Fermi level, providing valuable information on the spin transport behaviour.

**Spin Transport Measurements:** To assess the spin transport properties, techniques such as spin-polarized scanning tunnelling microscopy (SP-STM), spin valve measurements, and spin injection experiments are used. These methods can measure the spin diffusion length, spin relaxation time, and spin injection efficiency, which are essential parameters for evaluating SGS materials for spintronic devices.

***2.2.4. Device Fabrication and Testing:***

Once the materials are synthesized, thin films or microstructures of SGS materials are integrated into spintronic devices such as Spin-FETs, magnetic tunnel junctions (MTJs), and memory elements. The device performance is characterized using electrical measurements such as magnetoresistance (MR), current-voltage (I-V) curves, and spin polarization efficiency. These tests are critical to understanding the feasibility of SGS materials for practical applications in spintronics.

## 3. APPLICATIONS OF SPIN GAPLESS SEMICONDUCTORS

Spin-gapless semiconductors have immense potential for a variety of spintronic applications. The ability to manipulate electron spin and charge with minimal energy loss makes them ideal for several next-generation electronic devices. Some of the most promising applications are:

**Spin-Based Transistors:** Transistors are the building blocks of modern electronics. In spintronic transistors, the spin of electrons is used to control the flow of charge, in contrast to traditional transistors that rely on the charge alone. SGS materials, with their zero spin-gap and efficient spin transport properties, are ideal candidates for spin-based transistors. These transistors could outperform traditional charge-based transistors by providing faster switching times, lower energy consumption, and higher efficiency.

**Magnetic Random Access Memory (MRAM):** MRAM is a non-volatile memory technology that uses magnetic properties to store data. Spin-gapless semiconductors could be used in spin-transfer torque MRAM (STT-MRAM) devices, where spin-polarized currents are used to switch magnetic states, allowing for faster and more energy-efficient memory devices. The efficient spin injection and high spin polarization offered by SGS materials make them highly attractive for MRAM development.

**Spin-Injectors and Spin-Polarized Current Sources:** SGS materials are ideal for use as spin injectors in spintronic devices, where they can generate highly polarized spin currents without the need for ferromagnetic materials. This property is essential for devices such as spin valves, where the spin current is crucial for the operation of the device. The high spin polarization of SGS materials can significantly enhance the performance of spintronic circuits.

**Quantum Computing and Quantum Information Processing:** Quantum computing relies on qubits that use the quantum states of particles, including their spin, for computation. Spin-gapless semiconductors, with their ability to support stable spin-polarized currents, could play a significant role in the development of quantum processors. The spin coherence time in SGS materials is a critical parameter, and ongoing research is focused on optimizing this property for quantum applications.

**Thermoelectric Devices:** The high efficiency of SGS materials in transporting spin currents without significant charge dissipation makes them an excellent choice for spin-caloritronic devices, which involve the conversion of spin currents into heat or vice versa. These devices could be used in spin-based thermoelectric applications that harness waste heat for energy harvesting.

**Spin-Photonic Devices:** Spin-gapless semiconductors can be used in spin-photonic devices, where the spin current is coupled with optical photons to perform high-speed data transfer. The ability to manipulate both spin and charge simultaneously in these materials opens the door to high-speed data transmission and low-power communication technologies.

## 4. CHALLENGES IN SPIN GAPLESS SEMICONDUCTORS

While spin-gapless semiconductors offer significant promise, there are several challenges that need to be addressed before they can be fully integrated into spintronic applications:

**Material Synthesis and Fabrication:** The synthesis of high-quality SGS materials is challenging. For example, creating the

perfect conditions to maintain the zero-spin gap across the entire material is difficult. Additionally, controlling the uniformity of spin polarization across large-area films and achieving high-quality interfaces with other spintronic materials is a complex task.

**Spin Relaxation Times:** The spin coherence time and spin relaxation time in SGS materials need to be enhanced to allow for efficient spin transport over longer distances. Short spin relaxation times can result in loss of spin polarization, limiting the performance of devices like spin-based transistors and memory devices.

**Integration with Conventional Semiconductor Technologies:** The integration of SGS materials with traditional semiconductor materials, such as silicon, poses challenges due to the differences in material properties and the lack of a robust, scalable fabrication process. Ensuring compatibility and efficient interfaces between SGS materials and conventional electronics is crucial for the commercialization of spintronic devices.

**Temperature Sensitivity:** Many spin-gapless semiconductors require specific temperature conditions to maintain their spin-gapless properties, which limits their practical application at room temperature. Developing materials that maintain their spin-gapless nature at ambient temperatures is critical for large-scale use in commercial devices.

## 5. CONCLUSIONS

Spin-gapless semiconductors represent a promising class of materials for spintronic applications, offering the potential for faster, more efficient, and low-power devices. Their unique properties, such as zero spin gaps, high spin polarization, and semiconductor-like conductivity, make them ideal candidates for a wide range of applications, including spin-based transistors, MRAM, spin-injectors, quantum computing, and thermoelectrics.

Despite the significant potential, challenges remain in the material synthesis, spin coherence, and integration with existing technologies. Ongoing research into improving the spin transport properties, material quality, and scalability of SGS materials is essential for realizing their full potential in spintronic devices.

With continued advancements, spin-gapless semiconductors could play a pivotal role in the next generation of electronics, enabling breakthroughs in memory, computing, and energy-efficient technologies.

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